Investigations of abrasive wear of steel surfaces strengthened by vibro-arc carbonization/layering

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Friction and wear losses can be reduced by arc welding, tempering and other methods. One of these technologies is vibro-arc surface processing. By using this technology surface can be carbonized through the formation of extra layers with supplementary materials. The present work is an investigation of an opportunity to increase abrasive wear resistance of steel surfaces by carbonizing them by vibro-arc (80 and 120 A current) layering with a graphite electrode and by dip-transfer surfacing welded through layers that create paste-like coatings that consist of materials increasing resistance to wear. The investigations have been performed according to the standards of ASTM G65-94 – Dry Sand Rubber Wheel Abrasion Test, and ASTM G132 – Standard Test Method for Pin Abrasion Testing. Studies have shown that through surface carbonization layers are produced with a higher wear resistance than surfaces formed with the wear resistant powder PG-10N-01. When using carbonization, the wear resistance of steel surfaces increases by forming austenite synthetic ($Fe_{0,94}C_{0,06}$), cementite (Fe_3C), iron oxide ($Fe_{3,71}O_4$) structures. Even with the wear resistance increased up to 39–41%, the carbonization creates just thin layers of 0.1–0.15 mm. Surface welding with current pulses by using additional materials generates high temperature gradients. This deteriorates coating quality resulting in uneven thickness, formed cracks, voids. The formation of austenite synthetic ($Fe_{0,94}C_{0,06}$), cementite (Fe_3C), chromium nickel (Cr_2Ni_3), chromium iron carbide ($Cr_{21,34}Fe_{1,66}C_6$), carbon iron ($C_{0,09}Fe_{1,91}$) structures in a layer increases hardness (average 6145–6310MPa). Although the strengthened layer is much harder than steel Hardox 400, under abrasive wear conditions it has only 20–23% less wear resistance than Hardox 400. Due to surface defects, significant increases in hardness have almost no influence on the wear resistance. Surface quality is increased by welding at a lower current. Because just a thin layer is formed, the carbonization process is not an efficient technology to increase the abrasive wear resistance.

Keywords: vibroarc surface processing, carbonization and surface processing by welding, abrasive wear.

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INTRODUCTION

Electro-erosion machining, electro-spark deposition and other engineering technologies were created and developed in the XX century (see a review on the ex-USSR elaborations in [1]). However, without those developments the general technological progress would be unthinkable.

Electro-spark deposition has a wide range of technological potentialities in producing different coatings. In construction and agricultural machinery areas intensive abrasive wear dominates; for strengthening those machine elements technological methods are required that produce efficient and rather thick coatings [7, 9].

The essence of carbonization of steel with a graphite electrode by arc welding is hardening of the steel surface that is a result of periodical firing and extinguishing an electric arc (further — a pulsating arc). During electrode disintegration carbon diffuses into the steel surface. Because of rapid cooling the surface becomes tampered and in that way its important exploitation properties such as hardness, wear resistance and others get better [6].

The patent RU 2252266 describes steel surface carbonization that increases the microhardness of the surface layer to a depth of 1.2 mm by an electric arc with the reverse polarity when the arc is compressed by an inert gas stream to the value of the power density of 10^3 W/cm^2 [2]. Continuous burning of arc allows for getting deep strengthening but increases thermal impact, reduces the strength and deforms the product.

An additional wear resistant covering by vibro-arc processing is carried out in the paste-like layer composed of different materials (forming matrix of wear resistant components) and non-metals (flux) of powder mixtures. For example, metallic powder PG-10N-01 (basic metal – Ni; 0.8% C; 3.1% B; 4.2% Si; 17% Cr; 4.5% Fe) is used for gas-plasma deposition and arc welding [10].

The aim of the present paper is to present results on the use of vibro-arc processing when developing abrasive wear resistant layers on mild steel surfaces, and of the studies on their evaluation.

RESEARCH METHODOLOGY

Samples were made of the abrasive wear resistant steel Hardox 400. Samples were carbonized or welded using an inverter Foxweld Master 162 (open circuit voltage – 62 V, nominal welding voltage –

26.4 V, 80 and 120 A current and power density of 38 and 62 W/mm^2, respectively) with an electrode holder vibrator by using reverse polarity. Electrodes of 8 mm in diameter produced by the "GLOBAL WELDING COMPANY" were used in this study. Two technologies for vibro-arc processing of sample surfaces of steel Hardox 400 were used: surface carbonization with a graphite electrode by arc; and surface processing with a graphite electrode by arc, performed through the layer created as a paste-like coating that consists of a metal (nickel based welding powder PG-10N-01 and aluminum powder), ceramics (aluminum oxide, wolfram carbide and others), flux (made from molten glass, natrium borax [$Na_2B_4O_7 \cdot 10H_2O$] and others).

The abrasive wear resistance evaluation of both carbonized and welded surfaces was performed by two methods: 1. According to the standards of ASTM G65–94 – Dry Sand Rubber Wheel Abrasion Test [3], with a rubber wheel by using 0.25–0.4 mm fraction quartz sand (SiO_2); and 2. According to ASTM G132–96 (2007) – Standard Test Method for Pin Abrasion Testing [4], when a study of wear into fixed abrasive was done following the Standard (applying a „pin–on–cylinder“ scheme, under 28 N load).

The research method that follows ASTM G132–96 (2007) studies the wear into fixed abrasive parameters such as the feed of 0.55 mm/rev with a cylinder revolving 60 min^{-1} at the wear path of 100 m. The cylinder is coated with KX167, the abrasive paper roll grain (P100 grain abrasive paper from "Olympus Abrasives Co."), the average size of abrasive Al_2O_3 particles being 160 µm. The hardness of Al_2O_3 is 11.7 GPa.

The wear was evaluated by the method of masses with the scales KERN EG 420-3NM (accuracy 0.001 g).

Chemical composition of the samples was determined by a spectrometer BELEC-compact-lab-N. Hardness is measured with a microhardometer ПМТ–3, roughness – with a Surface Roughness Tester Series MahrSurf XR 20. Worn surfaces were analyzed with SEM JEOL JSM-5600, chemical composition was confirmed with the X-ray energy dispersion spectrometer Bruker XFlash 5040 QUAD Detector, crystallinity of layers – with X-ray diffractometer Bruker D8 with Cu K-alpha radiation.

The samples for testing microhardness by SEM were prepared according to standard methods. Before testing of the arc welded samples for abrasive wear resistance, slag and metal spray were mechanically removed.

RESEARCH RESULTS

The initial sample roughness was R_a 3.3 µm. The sample surface, processed by a graphite electrode with high frequency, showed the same roughness e– R_a 3.4 µm (sample *2*) or a little higher – R_a 6.2 µm (sample *1*) while working with a lower frequency.

Composite layers thickness received with vibro-arc welding can vary up to 2 times (0.6–1.2 mm), because of arc created variable pressure, what rips adjacent paste layers (Table 1) 5885–6405 MPa.

Spectral analysis data show that carbon content in the carbonized steel surface increases from 0.14% to 6.9% (sample *1*) and up to 2.8% (sample *2*, Table 1). Additionally, the carbonized layer was alloyed with boron, niobium and tungsten. In this case, the strengthened surface layer had the structure of white cast iron with the thickness of 0.1–0.15 mm and an average hardness of 2460 MPa (for Hardox 400) rising to 5410–6440 MPa. The hardness in the PG-10N-01 matrix welded layer varied from 6140 to 6310 MPa (samples *3* and *4*, Table 1). High hardness dispersion showed an unequal distribution of carbide structures and surface defects.

Standard X-ray diffraction studies of a sample from Hardox 400 show only iron peaks (Fig. 1, Standard). Surface carbonization with a graphite electrode results in the formation of cementite (Fe_3C), austenite ($Fe_{0.94}C_{0.06}$), and iron oxide ($Fe_{3.71}O_4$) structures (diffractograms in Figs. 1.1 and 2). Thus formed structures increase the abrasive wear resistance [5]. Because of a thin layer (just 0.1–0.15 mm), the shortening of time in the experiment up to 2 minutes was effective in determining the real carbonization impact for Hardox 400 steel resistance to abrasive wear – the wear reduced up to 41% (Table 2).

Welding with 120 A current (sample *4*) allows to work more productively, but increases the iron content of the sample surface from 22.7 up to 54.6% (Table 1). In the base metal and the coating intermingling, the surface can deteriorate its wear resistance, while adhesion increases. This is demonstrated by the coating of sample *4* whose wear is 5–18% higher, in accordance with ASTM G65-94 (Table 2).

Welding with a higher current increases carbon content and decreases contents of nickel, aluminum, and silicon in layers. The amount of oxygen does not change. A higher current creates material losses (sprinkle, burning).

The carbonized layer is thin and, in the long run, the impact of abrasive is inefficient. A test by ASTM G65 shows higher wear for the vibro-arc welded layer than for the carbonized layer (Table 2). This is related to the layer heterogeneity, removal of metal particles spatter at the beginning of test, of slag residues, high strain of layer, as well as deep mobile abrasive particle penetration. Harder wear of the arc welded layer compared with that of Hardox 400 steel – cause higher contact load, resulting from the high-alloyed surface heterogeneity.

Table 1. Chemical composition, hardness and depth of strengthening of layers

Sample	Sample	Chemical composition, %	Average hardness, MPa	Depth of strengthening, mm
Standard	Hardox 400	0.14 C; 0.35 Si; 1.0 Mn; 0.21 Cr, 0.03 W, 0.002 B	2310–2610	–
1	Hardox 400, carbonized with low frequency	6.89 C; 0.59 Si; 0.71 Mn; 0.2 Cr, 0.2 W; 0.05 Ti; 0.013 B; Nb 0.017.	4510–6310	0.09–0.10
2	Hardox 400, carbonized with high frequency	2.78 C; 0.33 Si; 0.8 Mn; 0.11 Cr, 0.006 B; 0.013 Nb; 0.05 W.	5590–7290	0.14–0.15
3	Layer welded through paste-like coating, at 80 A	45.0 Ni; 22.7 Fe; 17.0 Cr; 7.1 Si; 3.6 O; 3.7 C; 0.8 Al.	5885–6405	0.6–1.2 (has defects – craters, cavities)
4	Layer welded through paste-like coating, at120 A	54.6 Fe; 22.5 Ni; 8.3 Cr; 4.5 Si; 3.6 O; 6.2 C; 0.4 Al.	5310–7310	0.5–0.7 (has defects – cracks, cavities)

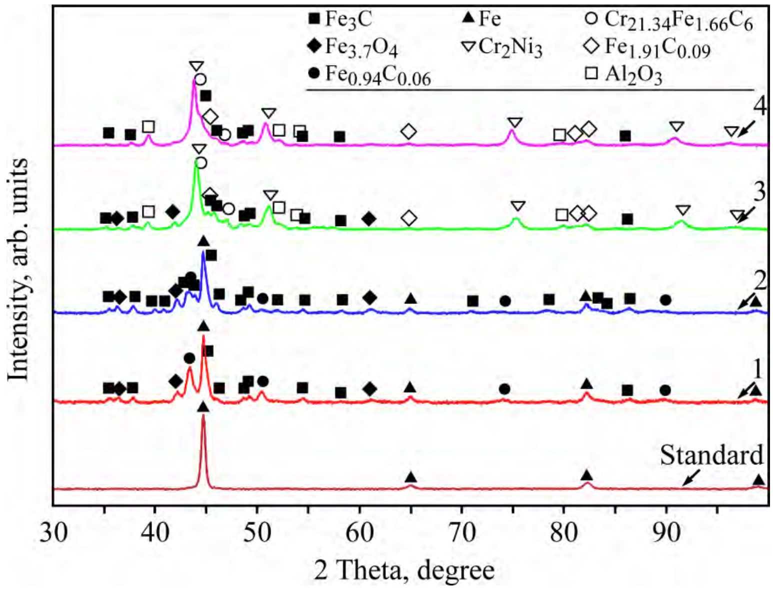


Fig. 1. Hardox 400 Steel, carbonized Hardox 400 and welded layers diffractograms: Standard –Hardox 400 steel; 1 – Hardox 400 carbonized with 80 A current; 2 – Hardox 400 carbonized with 120 A current; 3 – welded with 80 A current; 4 – welded with 120 A current, markings: ▲ – iron(Fe); ♦ – iron oxide ($Fe_{3.71}O_4$); ● – austenite synthetic ($Fe_{0.94}C_{0.06}$); ■ – cementite (Fe_3C); ▽ – chromium nickel (Cr_2Ni_3); ○ – chromium iron carbide ($Cr_{21.34}Fe_{1,66}C_6$); ◊ – carbon iron ($C_{0.09}Fe_{1.91}$); □ – aluminium oxide (Al_2O_3).

Table 2. Abrasive wear results of carbonized and welded samples

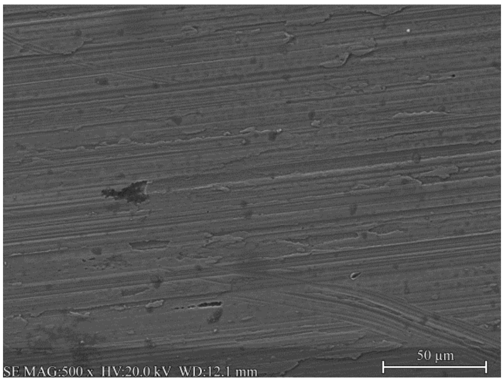
Sample	Sample processing, material	Wear, *g* (wear change, % – reduced, + increased), parameters when testing		
		ASTM G65-94		
		F_{load} = 100 N, t = 10 min	F_{load} = 45 N, t = 5 min	F_{load} = 45 N, t = 2 min
0	Hardox 400	0.157	0.041	0.022
1	Hardox 400 carbonized with low frequency	0.155 (-1.3%)	0.032 (-22%)	0.013 (-41%)
2	Hardox 400 carbonized with high frequency	0.134 (-14.6%)	0.025 (-39%)	0.015 (-32%)
3	Layer welded through paste-like coating, at 80 A	0.178 (+13.4%)	0.053 (+29.3%)	0.021 (-4.5%)
4	Layer welded through paste-like coating, at 120 A	0.205 (+30.6%)	0.055 (+34.1%)	0.025 (+13.6%)
		ASTM G132–96 (2007)		
		F_{load} = 28 N, t = 6 min	F_{load} = 28 N, t = 3 min	
1	Hardox 400	0.497	0.293	
3	Layer welded through paste-like coating, at 80 A	0.436 (-12.3%)	0.238 (-18.8%)	
4	Layer welded through paste-like coating, at 120 A	0.381 (-23.3%)	0.293 (-20.1%)	

In analyzing the wear by a fixed abrasive, it was found out that the welded layer is more wear-resistant (12.3 and 23.3%) than Hardox 400 steel. The reason for this is significantly increased layer hardness due the Fe_3C, Cr_2Ni_3, Al_2O_3 components formation (Fig. 1).

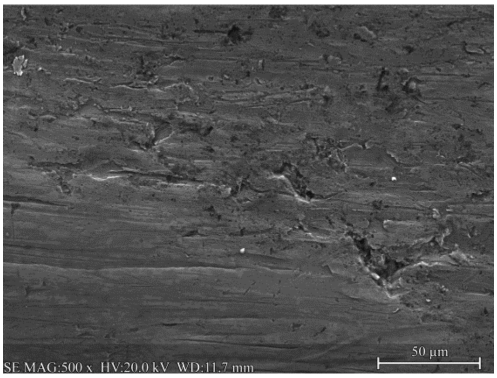
Shortening the duration of the test, performed by ASTM G132-96, shows no influence on the results for layers welded with 80 and 120 A currents.

Abrasive wear test results performed according to ASTM G65-94 and ASTM G132-96 by using different test parameters are given in Table 2.

The wear of Hardox 400 steel is smooth, the carbonized layer is sleek, and in the junction with the basic metal a phase is formed where wear is intensive (Fig. 2).



(a)

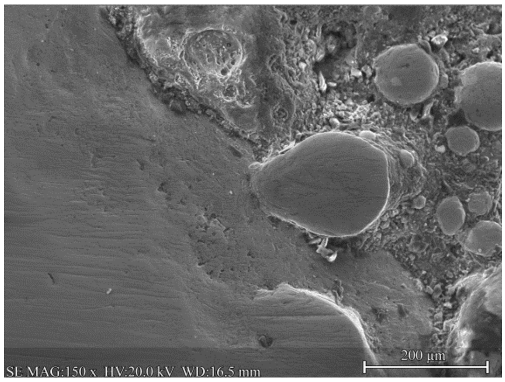


(b)

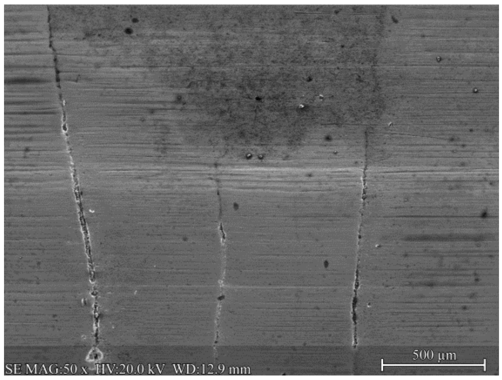
Fig. 2. SEM images after ASTM G65 (500×): (a) Hardox 400 steel; (b) strengthened Hardox 400 steel, sample *2*.

Optical evaluation of cross-section of micro polished arc welded layers shows good adhesion between the coating and the substrate, mixing, minimal thermal effects, even the carbide phase distribution (Fig. 4).

The arc welded layer has many defects (Fig. 3) (metal droplets, cracks), which during ASTM G65 test with free abrasive particles can go deeper thus the wear is higher. Meanwhile during ASTM G132–96 tests, only arc welded layer "caps" contact with the abrasive paper and the wear is lower (12.3–23.3%), compared with Hardox 400 steel (Table 2).



(a)



(b)

Fig. 3. SEM images of welded layers: (a) heterogeneous surface with a metallic spatter (sample *3*, 150×); (b) cracks of arc welded layer (sample *4*, 50×).

In both cases, that is, carbonization and arc welding, the surface hardness increased significantly (Table 1), but wear reduced for just a few tens of percents. It can be explained by small difference in test sample materials and abrasive hardness ratio (H_M/H_A) [8].

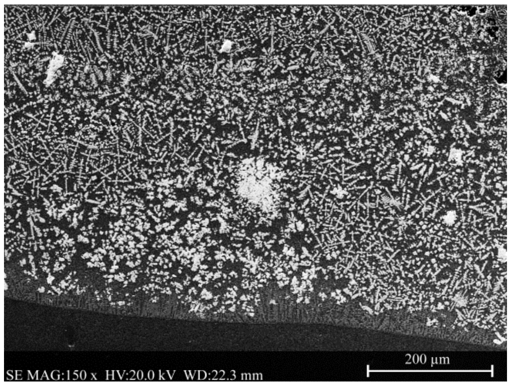


Fig. 4. SEM images of welded layers (sample *3*, 150×).

CONCLUSIONS

The research into impulsive steel surface processing shows that:

1. Steel surface strengthening with a graphite electrode is advisable for increasing durability to friction pairs, where 0.1–0.15 mm wear is permissible (the wear can be reduced up to 41%); the wear is reduced because of the formation of cementite, aus-

tenite compositions, which increases hardness from 2460 to 5410, even 6440 MPa.

2. Vibro-arc welding with the composite Fe-C-Ni-Cr-Si-Al and the layers thickness of 0.6–1.2 mm is advisable for wear resistance to a fixed abrasive because the wear reduces up to 23.3%; therefore it is more objective to test layers with defects with a fixed abrasive.

3. Increasing the welding current from 80 to 120 A reduces the layer uniformity, increases the basic metal fusibility (in the layer iron content increases and that of nickel decreases), but the resistance to wear does not change.

4. It is essential to increase welding quality and to get fewer layer defects such as variable layer thickness, cracks, cavities.

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Реферат

Для уменьшения величины трения и износа трущихся деталей применяются новые материалы, смазки, наплавки; используются также металлизация, гальваническое покрытие, термическая обработка. В данной работе рассматриваются возможности увеличения стойкости деталей к абразивному изнашиванию путем упрочнения/нанесения покрытий вибродуговой нап-лавкой графитовым электродом. Вибродуговым науглероживанием графитовым электродом и наплавкой покрытий через порошковые (пастообразные) слои было произведено упрочнение поверхностей образцов. Обработка поверхностей проведена токами величиной 80 и 120 ампер. Исследования сопротивления абразивному изнашиванию выполнены согласно требованиям стандартов ASTM G65-94 и ASTM G132-96 (2007). Полученные результаты свидетельствуют о том, что науглероженные графитовым электродом слои являются более стойкими к абразивному изнашиванию, чем исходная сталь Hardox 400 и чем слои, наплавленные через пастообразное покрытие на основе порошка ПГ-10Н-01. Науглероживание малоуглеродистой стали Hardox 400 графитовым электродом увеличивает количество углерода до 2,8–6,9% и формирует аустенитную ($Fe_{0,94}C_{0,06}$) и цементитную (Fe_3C) поверхностные структуры, а также оксидирует поверхность ($Fe_{3,71}O_4$). Это снижает абразивный износ до 39–41%, но науглероживанием формируются слои толщиной 0,1–0,15 мм. Наплавка импульсной дугой поверхностей образцов через слои дополнительных материалов создает импульсное воздействие на наплавляемый материал, разрушает слой, вследствие чего формируются слои неравномерной толщины с трещинами, порами, кратерами. Композиционное покрытие на основе порошка ПГ-10Н-01 формирует аустенитную ($Fe_{0,94}C_{0,06}$), цементитную (Fe_3C), хромникелевую (Cr_2Ni_3) структуры, карбиды хрома-железа ($Cr_{21,34}Fe_{1,66}C_6$), карбиды железа ($C_{0,09}Fe_{1,91}$), которые обеспечивают твердость покрытия в интервале 6145–6310 MPa. Хотя твердость покрытий существенно выше твердости стали Hardox 400, в условиях абразивного изнашивания покрытие имеет износ только на 20–23% меньше износа Hardox 400. Причиной такой незначительной разницы является большая дефектность покрытий. Качество покрытия снижает и наплавка большими импульсными токами. Наиболее целесообразным применением упрочненных науглероживанием слоев являются сопряжения, допустимый износ которых не более толщины упрочненных слоев, а вероятность попадания абразивных частиц в сопряжения мала.

Ключевые слова: вибродуговая обработка поверхностей, науглероживание и наплавка поверхностей, абразивный износ.